The Optimal Design for SMART Reactor Cover

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ABSTRACT

The reactor pressure vessel of the nuclear power plant has been made of carbon steel because of its high strength. Since the central cover of SMART(System-integrated Modular Advanced ReacTor) includes many penetrations for various components, pipings and instrumentations, it is very difficult to clad on the surface of small holes after machining. If the central cover is made of stainless steel, both the corrosion problem and the cladding difficulty may be overcome and the manufacturing cost will be reduced. In this paper, the stainless steel central cover is analyzed using 2-D axisymmetric model, 3-D equivalent solid plate model and 3-D real model with holes by ANSYS and IDEAS code. The analysis results show that the stainless steel central cover meets requirements of Section III ASME Code for the design pressure loading. Also, the optimization for the reactor cover which consists of a central cover and an annulus cover was performed   using ANSYS code.

INTRODUCTION

The reactor pressure vessel for the nuclear power plant has been made of carbon steel because of its high strength. Stainless steel cladding is normally applied on the coolant-contact-surface of the carbon steel pressure vessel since carbon steel is highly susceptible to the reactor environment producing corrosion. The central cover of SMART includes relatively many penetrations for various components, pipings and instrumentations (Fig.1,2). This makes it difficult to keep a conventional design of carbon steel with stainless steel cladding. If the central cover of whole stainless steel body is adopted, both the corrosion problem and the manufacturing difficulty are to be solved and the manufacturing cost will be reduced. However, the structural integrity of the stainless steel central cover remains still unverified since yield strength of stainless steel is   generally lower than that of carbon steel.

In this paper, to check whether the stainless steel central cover is to withstand the 17 MPa of the design pressure, the stainless steel central cover was analyzed by IDEAS [1] and ANSYS code [2] using a 2-D axisymmetric solid element. The procedures of analyses were made in accordance with the ASME Code [3]. Also, the central cover was modeled using 3-D equivalent solid plate and 3-D real plate with holes by IDEAS code [4-6]. Also, to get the optimal shape of the reactor cover which consists of a central cover and an annulus cover, the optimization was performed using ANSYS code.

ANALYSIS OF 2-D AXISYMMETRIC MODEL

Analysis Model and Analysis Method

The dimension of the central cover (Fig.2) is the diameter 2210 mm and the minimum thickness 353 mm. The central cover should meet the design condition of ASME Code, Section III NB3221.

$$P_m < S_m , \quad P_L < 1.5\,S_m , \quad P_L + P_b < 1.5\,S_m$$

where, P_m = general membrane stress, P_L = local membrane stress, P_b = bending stress, S_m = stress intensity

The design pressure and the temperature of the central cover is 17 MPa and 150 ℃, respectively. Three materials for the analysis of the central cover are considered and mechanical properties are as follows [7].

Table 1. Material Properties

	Austenitic Stainless Steel		Carbon Steel
	SA 240, Type 321	SA 336,Class F321	SA 508, Class 4
Yield Strength (MPa)	205	207	483
Modulus of Elasticity (MPa)	173,103	173,103	183,448
Poisson's Ratio	0.27	0.27	0.3
Stress Intensity (MPa) at 150 $^\circ$C	138	138	206

The central cover was modeled and analyzed using IDEAS code. Also, IDEAS modeling INPUT was converted to ANSYS INPUT and the central cover was analyzed using ANSYS code. 2-D axisymmetric solid elements were used for modeling. The x, y, z displacements of the face contacted with the segment gate and x, z displacements of the face contacted with the torus ring were fixed in Fig. 3. The central cover with holes can be converted to the equivalent solid plate by the A-8132.4 (15) formula of the reference 8. The ligament efficiency of the central cover was as follows.

$$\eta = h / P = \{h + (2\ Et/E)\ tt\} / P = 0.586$$

Effective Young's modulus and Possion's ratio were estimated by Fig. A.8131-1 of reference [8]. These values were E^* =108,179 MPa and $\nu^* = 0.29$, respectively. Also, the hoop stress of the equivalent solid plate was considered.

$$Spi = \sigma_r = \sigma_\theta = \{h / P\}\ \{(P - h - 2\ tt) / [h + 2\ (Et/E)\ tt]\}\ p_i = 4.468\ \text{MPa}$$

Analysis Results

1) Analysis Result of ANSYS

The analysis was calculated at three sections as shown in Fig. 3 and these results were as follows.

Table 2. Results of Finite Element Analysis using ANSYS

	P_m (MPa)	$P_m + P_b$ (MPa)
cut 1 section	35.640	183.807
cut 2 section	84.357	100.324
cut 3 section	86.057	134.112

2) Analysis Result of IDEAS

Analysis Results of IDEAS Code represented the maximum principal stress (Max. σ_I), as 105 MPa and the maximum shear stress (τ_{max}) as 58.6 MPa. The distribution of maximum shear stress was shown in Fig. 4.

ANALYSIS OF 3-D MODEL

Analysis model of 3-D equivalent solid plate

1) Analysis model and analysis method

The central cover was modeled using 3-D equivalent solid plate without holes. Effective Young's modulus and Possion's ratio were estimated by Fig. A.8131-1 of reference [8]. These values were E^* =108,179 MPa and $\nu^* = 0.29$. The

applied load was 17 MPa of the internal pressure. The finite element model of 3-D equivalent solid plate was shown in Fig. 5.

2) Analysis Results

Analysis results of IDEAS code represented the maximum principal stress (Max. σ_l) as 66.5 MPa and the maximum shear stress (τ_{max}) as 62.5 MPa. The distribution of maximum shear stresses was shown in Fig. 6.

Analysis model of 3-D real plate

1) Analysis model and analysis method

Since the central cover with holes is axisymmetric with respect to center line, 1/4 part of that was only modeled. Applied loads were 17 MPa of the internal pressure and 26650 kg_f of the weights of 41 CEDM (Control Element Drive Mechanism). This analysis result was shown in Fig. 7.

2) Analysis Results

Analysis results of IDEAS code represented the maximum principal stress (Max. σ_l) as 143 MPa and the maximum shear stress (τ_{max}) as 80 MPa. The distribution of maximum shear stresses was shown in Fig. 6. The weights of 41 CEDM did not affect the distribution of stress. The distribution of maximum principal stresses and maximum shear stresses were shown in Fig.7 and Fig. 8, respectively.

REVIEW OF 2-D AND 3-D ANALYSIS RESULTS

2-D Axisymmetric Model

The highest membrane stress (P_m = 86.057 MPa) represented along the cut 3 section and this value was below the allowable stress intensity of the austenitic stainless steel A240 (S_m = 138 MPa). The highest a membrane stress plus a bending stress ($P_m + P_b$ = 183.807 MPa) represented along the cut 1 section and this value was below the allowable stress intensity of the austenitic stainless steel A240 (1.5 S_m = 207 MPa). Therefore, the stainless steel central cover analyzed meets the requirements of ASME code in design condition.

3-D Analysis Model

1) Analysis model of 3-D equivalent solid plate

The location of the highest principal stress in the central cover was the face contacting with the segment gate. Therefore, the high tensile steel should be used as the materials of the segment gate. Since the maximum principal stress of 2-D axisymmetric model was higher than that of 3-D equivalent solid plate model, the analysis results of 2-D axisymmetric model is more conservative. Comparing the shear stresses of 2-D axisymmetric model (Fig. 4) with those of 3-D equivalent solid plate model (Fig. 6), those levels and the distribution of stresses were almost same. Therefore, the analysis results of 2-D axisymmetric model were more conservative.

2) 3-D real plate model

The maximum principal stresses and shear stresses of this model represented near holes and the distribution of these were very local. Also, since all values were below the yield stress of the austenitic stainless steel A204, the central cover in structural view is safe. Since the stress levels of 3-D real plate model and 3-D equivalent solid plate model were almost same, 2-D axisymmetric model and 3-D equivalent solid plate model were suitable for the estimation of the structural integrity in comparing with 3-D real plate model.

OPTIMAL DESIGN OF REACTOR COVER

Analysis Model and Analysis Method for Optimal Design

The radius of a reactor cover (a central cover and an annulus cover) is 1850 mm and thickness is 350 mm. The initial shape for the optimization is shown in Fig. 9. Also, the reactor cover was modeled using 2-D axisymmetric solid element and the equivalent solid plate (E^* =108179 MPa, $\nu^* = 0.29$). The optimal works were performed by ANSYS Code. Applied load was 17 MPa of the internal pressure and the model was divided into 5 sections. The design variable for the optimization is the thickness of the model and the initial thickness of this model is 350 mm, that is, T1 = 350, T2 = 350, T3 = 350, T4 = 350, T5 = 350. When the principal stress was selected as the state variable for the optimization, the value is restricted within 170 MPa and the maximum displacement is restricted within 3.5 mm. Also, when the stress intensity was selected as the state variable for the optimization, that value is restricted within 200 MPa and the maximum displacement is restricted within 3.5 mm. The objective function is the volume of the reactor cover, which is minimized for the optimization.

Analysis Results

Case (1) : The result of the case restricted within the principal stress: 170 MPa and maximum displacement: 3.5 mm (Fig. 10)
Case (2) : The result of the case restricted within the stress intensity: 200 MPa and maximum displacement: 3.5 mm.
The result values for the design variable minimized the volume of the reactor cover were as follows.

Table 3. Results of Optimal Design for Reactor Cover

Design Variable	Case (1) (mm)	Case (2) (mm)
T1	919.42	919.18
T2	436.41	477.60
T3	436.90	392.63
T4	515.66	457.84
T5	435.07	350.00
T6	350.00	350.00

CONCLUSIONS

1) The analysis results of the stainless central cover met ASME Code, Section III, NB3221 design condition. Therefore, the structural integrity of that was verified in the preliminary design. The weights of 41 CEDM in 3-D real plate model did not almost affect the stress distribution of the central cover. 2-D axisymmetric model and 3-D equivalent solid plate model were suitable models for the estimation of the structural integrity in comparing with 3-D real plate model.
2) The shape to minimize the volume of the reactor cover was obtained using ANSYS Code and that will be reflected in the detail design.

ACKNOWLEDGEMENT

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7. ASME Code, Section III Appendices, Table I-1.2, 1995.
8. ASME Code, Section III, Division1-Appendicies, 1995.
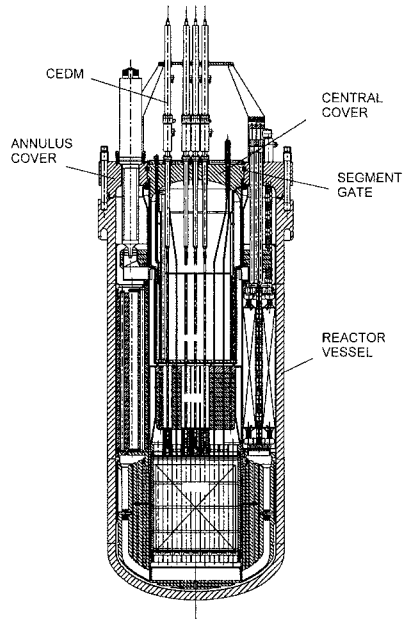
Fig. 1   SMART Reactor Assembly
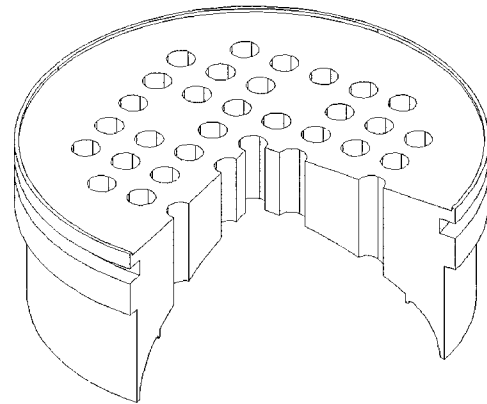
Fig. 2   Central Cover
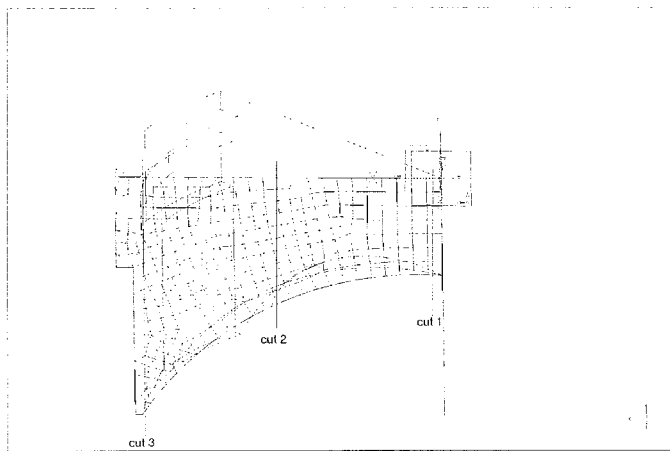
Fig. 3   2-D Axisymmetric Model
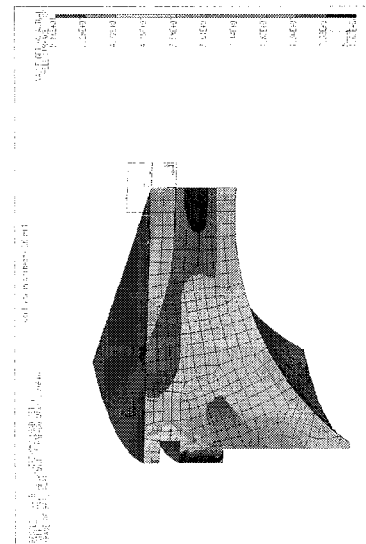
Fig. 4   Distribution of Max. Shear Stress (2-D)
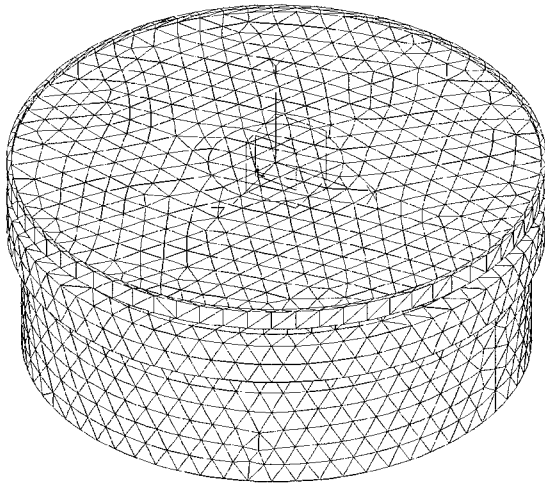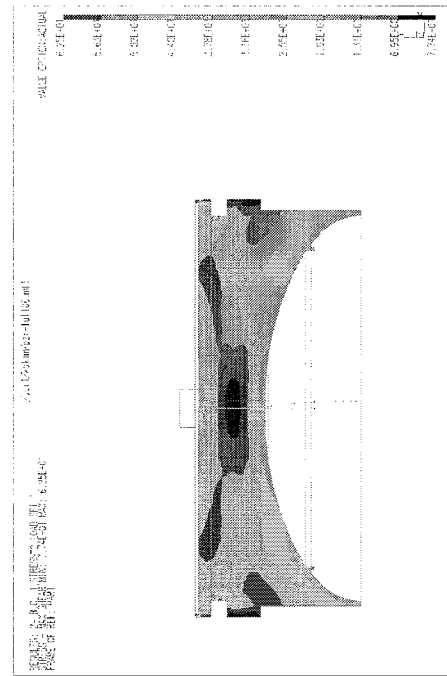
Fig. 5　3-D Equivalent Solid Plate Model

Fig. 6　Distribution of Max. Shear Stress
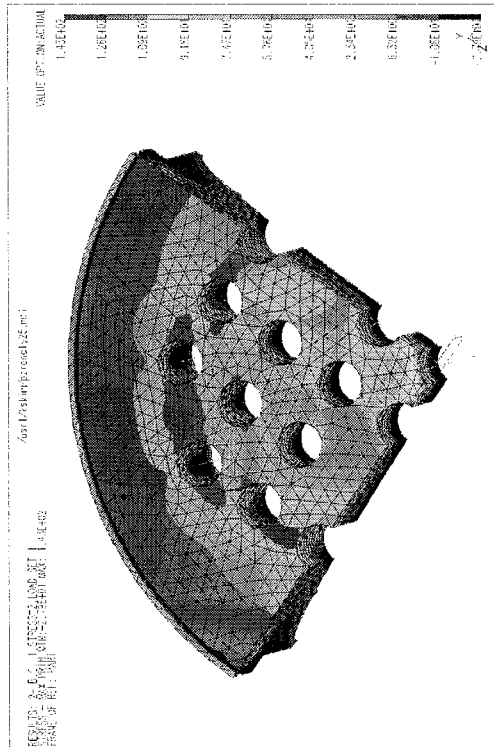(3-D Equivalent Solid Plate Model)

Fig. 7　Distribution of Max. Principal Stress
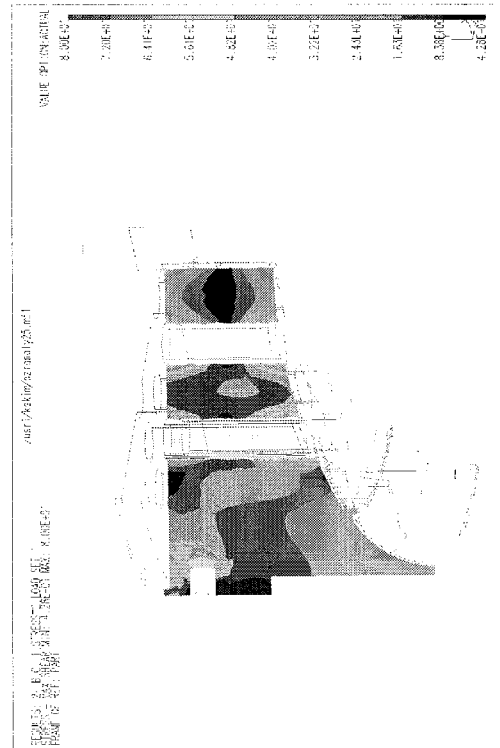(3-D Real Plate Model)

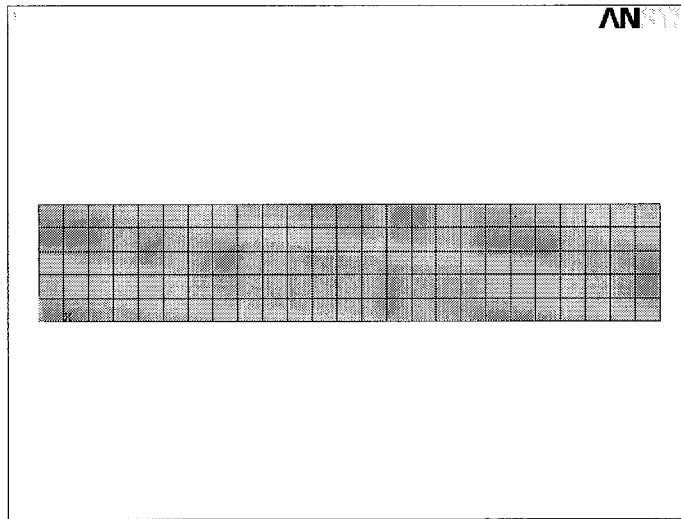Fig. 8　Distribution of Max. Shear Stress
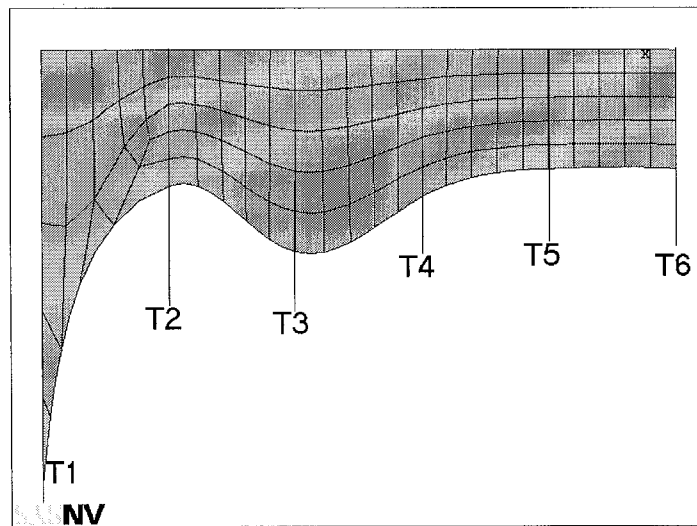(3-D Real Plate Model)

Fig. 9   Initial Shape of Reactor Cover

Fig. 10   Result of Optimization (Case 1)